New Nucleosynthesis Process Discovered in the Crust of Neutron Stars

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Neutron stars (NS) are unique stellar laboratories for the study of matter at the most extreme density and exotic neutron-rich nuclei. However, finding a unique observable feature of neutron stars that can directly probe these properties has been challenging. In the past decade, observations of neutron stars in X-ray binary systems, where the NS accretes matter (hydrogen/helium) from a companion star, have provided promising new insights about various nuclear burning phases on the NS surface and deeper inside the crust. Thermonuclear burning on the NS surface occurs through a sequence of rapid proton (rp) captures, the rp-process, and powers the light curves of the commonly observed Type I X-ray bursts. As ashes of the rp-process sink deeper into the NS under the weight of freshly accreted matter, they undergo electron capture (EC) reactions that convert the proton-rich nuclei to increasingly neutron-rich nuclei—the energetically favored state in the neutron star crust. Eventually, with increasing depth, the EC proceeds to the point where neutron-rich nuclei begin to lose neutrons into the continuum beyond a certain density called the "neutron-drip" point.

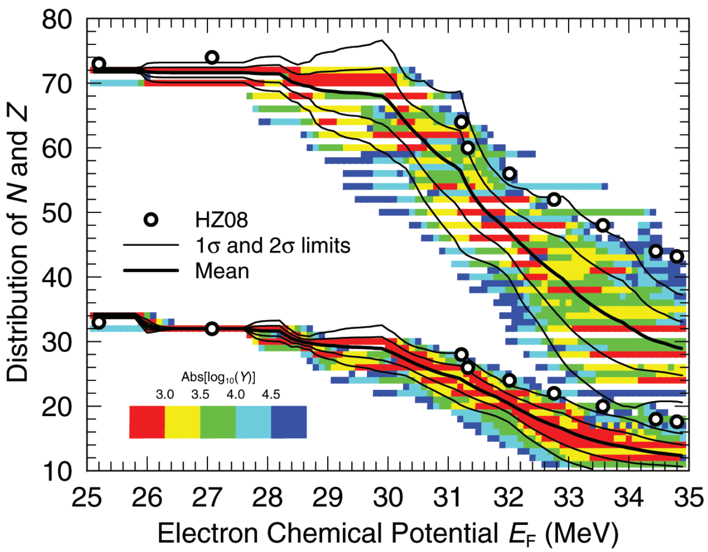

Fig. 1. Heterogeneity (a spread in proton number along the y-axis) will be retained in the NS Crust due to nuclear shell structure effects affecting the newly discovered SEC process of nucleosynthesis. This spread is shown as a function of depth in the NS (denoted by increasing electron Fermi energy in MeV along the x-axis).

Nuclear reactions that convert proton-rich ashes into neutron-rich nuclei in the crust directly impact thermal properties of the outer regions of the neutron star. This in turn is critical to interpreting observations of explosive events such as X-ray bursts and superbursts, and also the quiescent thermal luminosity of transiently accreting NS. The nuclear reactions not only determine where and how efficiently energy is released to heat the crust, but also how efficiently the heat can be conducted in the crust or radiated away in neutrinos. This is because thermal conduction and neutrino cooling rates have a sensitive dependence on the composition of nuclei produced by these nuclear reactions. Until recently, both the heat release and the composition in the crust were poorly known, and depended sensitively on the composition of the initial rp ashes.

The authors have calculated for the first time the composition of matter in an accreting NS post-neutron drip using modern nuclear structure and reaction information for exotic neutron-rich nuclei. This published work [1] uses a large reaction network to follow the heterogeneous X-ray burst ashes as they sink deeper in the NS crust. The multicomponent plasma simulation unearths a new nucleosynthesis process, named the Superthreshold Electron capture Cascade (SEC) process in [1], which shows that heterogeneity (a spread in proton number) will be retained in the NS Crust due to nuclear shell structure effects. This spread is shown in Fig. 1 as a function of depth in the NS (denoted by increasing electron Fermi energy in MeV). The efficiency of the SEC process in heating the NS crust as a function of depth is shown in Fig. 2 where the cumulative SEC heatings in units of MeV/accreted baryon from different initial crust compositions (xM and XM) are compared with the heating from the one-component plasma simulations (HZ08) that exist in the literature. Interestingly, this new finding also suggests that the composition and heating in accreting neutron star crusts are fairly insensitive to the initial crust composition resulting from the rp-process on the NS surface. This is a major breakthrough because it strongly constrains theoretical models needed to interpret the observations, thereby allowing us to probe fundamental questions about the state of matter inside neutron stars.

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[1] S.S. Gupta, P. Möller, T. Kawano, *Phys. Rev. Lett.* **101,** 231101 (2008).

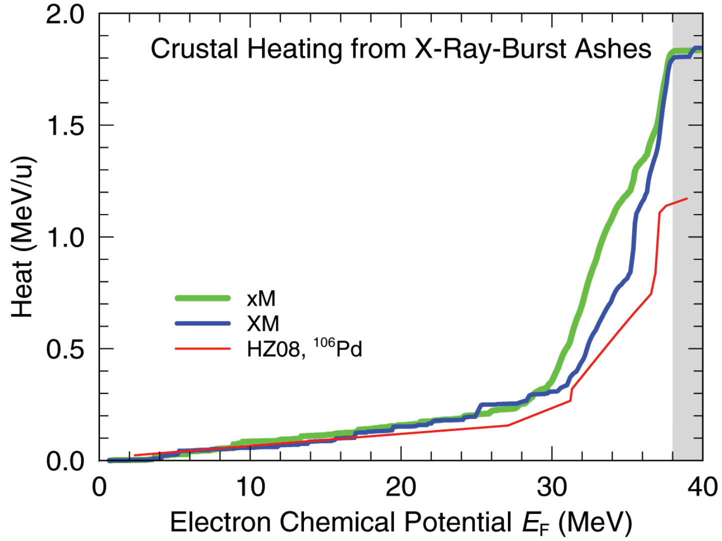

Fig. 2. The efficiency of the SEC process in heating the NS crust as a function of depth. The cumulative SEC heatings in units of MeV/accreted baryon (along the y-axis) from different initial crust compositions (xM and XM) are compared with the heating from the one-component plasma simulations (HZ08). The x-axis has the same meaning and units as in Fig. 1.

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